Manager's brief: Integrating fire refugia concepts and data into vegetation management decisions

A case study on the Gifford Pinchot National Forest, Little White Salmon Project Area, Washington

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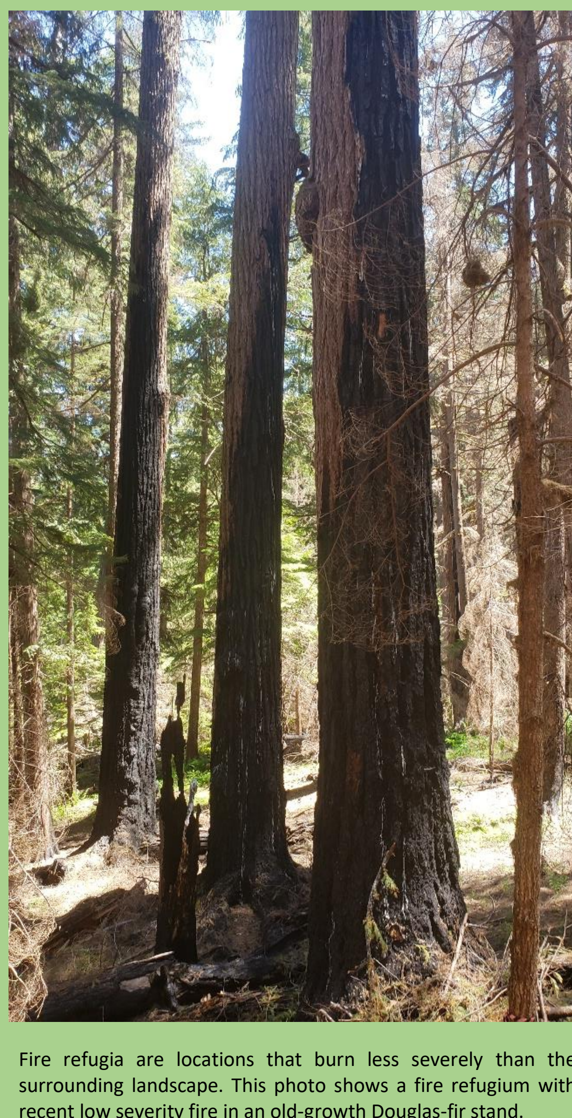

Fire refugia are locations that burn less severely than the surrounding landscape. This photo shows a fire refugium with recent low severity fire in an old-growth Douglas-fir stand.

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Executive summary

Concepts and models of fire refugia are increasingly a part of forest management discussions in the context of wildland fire and global change. However, translating new science and data products to management decisions and treatment prescriptions is not an easy task. These applications can be better informed by collaboration between scientists and managers to identify best uses of new data products, and spending time creatively discussing and integrating the "so what?" from science into decisions on the ground. Scientists and managers from the US Forest Service Little White Salmon Forest Resilience and Wildfire Risk Mitigation Project area on the Gifford Pinchot National Forest and Washington State Department of Natural Resources (WA DNR) worked collaboratively with Oregon State University scientists to develop this manager's brief to facilitate integration of fire refugia science into forest project planning, providing a case study for actionable science and a template for future projects using fire refugia concepts across the region.

The fire refugia manager's brief covers two objectives outlined by the Little White Salmon (LWS) project team, as key elements required to effectively integrate fire refugia concepts and products into project-level planning. The first objective is a synthesis tailored to the manager audience describing:

1. *What are fire refugia?* We summarize the concept of fire refugia as locations on the landscape burned less severely and/or less frequently than surrounding areas, and provide an overview of how these concepts can be considered in relatively moist vs. dry landscape settings. We emphasize that our challenge is to identify information on fire refugia pertinent to land management goals and tailored to the focal ecosystem.
2. *What products are currently available to map fire refugia in the region?* We introduce the holistic fire refugia models and the topo-climatic fire refugia models, describe their key components and how they complement each other in the context of refugia science. We briefly introduce the WA DNR Large Dense Forest Sustainability maps and their relationship to fire refugia, and connect all of the work to cornerstone research by Camp et al. (1997) on fire refugia in the Swauk Late-Successional Reserve.
3. *What are the drivers of fire refugia?* We provide a short summary of the models and important variables that contribute to the holistic fire refugia and topo-climatic fire refugia products. We describe the vegetation/fuels, topography, fire weather, and fire growth components of the holistic fire refugia models, and describe the topography and climate components of the topo-climatic fire refugia models.
4. *Where are fire refugia located in the Little White Salmon project area?* We produce maps of the LWS area to showcase fire refugia products in the Resilience Block and High Risk Block of the project area, illustrate multiple scenarios of the holistic fire refugia and topo-climatic fire refugia models, and develop an example of how overlays of the scenarios can provide interpretations valuable for vegetation management decisions.

The second objective was to engage with LWS scientist and manager partners to discuss and summarize potential implications of vegetation management treatments on fire refugia characteristics, including understanding of:

5. *How do fire refugia overlap with other highly valued resources in the LWS project area?* We provide ideas for the types of data that could be useful for map analysis with fire refugia products, and provide an example for using map products of OGSI80 and OGSI200 (mature and old-growth forests) and fire refugia products to inform management decisions and planning.
6. *What do fire refugia models tell us about management at the stand and watershed scale?* We use a Frequently Asked Questions (FAQ) approach to illustrate ideas that can contribute to ongoing community discussion and decisions integrating fire refugia data. We emphasize that the FAQ does not represent prescriptive or comprehensive coverage of the information, but starts a conversation on ideas based on academic and management expertise.
7. *How could forest management increase the extent and sustainability of refugia?* We continue the FAQ format to illustrate ideas for management informed by fire refugia products.

The report concludes with:

8. *Additional resources on fire refugia*. We provide a collection of resources related to fire refugia concepts, including links to data products, webinars, copies of journal articles, links to websites, etc.

We look forward to ongoing evolution of conversations and implementation of fire refugia concepts and data within this community of practice, supporting effective management decisions in the context of climate change.

1. What are fire refugia?

Fire refugia are locations on the landscape burned less severely and/or less frequently than surrounding areas (Camp et al. 1997, Meddens et al. 2018, Krawchuk et al. 2020). Meddens et al. (2018) provide a taxonomy that unpacks nuances of fire refugia based on severity of burning (unburned to lower severity), predictability of occurrence (predictable to stochastic patterns), spatial scale of the pattern (from individual plant to stands, landscapes, and regions), and persistence (one fire event to multiple fire events). All of these features of fire refugia are important and can have different ecological implications. One way to avoid confusion in talking about fire refugia is to use the phrasing "*from* what *for* what", similar to best practices in using the term resilience. What this brief focuses on is identifying predictable refugia *from* high-severity fire *for* existing and potential mature and old-growth forests.

Recognizing that fire refugia terminology can be used for locations that burn at low severity when the surrounding area experiences higher severity fire, as well as locations that are truly unburned, is important for the application of fire refugia science. Lower severity fire, or underburning, dominated by surface fire may be a critical ingredient for maintaining fire refugia across a broad geography of forest types. This is certainly true for historically frequent-fire ecosystems, where chronic low-severity fire anchored the dry forest system as a refugium from large patches of high-severity fire and maintained open canopy, old forest characteristics across large areas (e.g., Hagmann et al. 2021). With fire exclusion in fire-prone landscapes, later-successional forest conditions have developed, but these stands are not in the right place (terrain position) to provide microclimate and vegetation structure conducive to fire refugia through most fire events. These "apparent" closed canopy fire refugia (Camp et al. 1997) may be vulnerable to stand-replacing fire, insects, and pathogens/disease (Hessburg et al. 1994) and should be prioritized for restoration and adaptation silvicultural treatments in drier forest types or where open forest conditions are a desired objective. Additionally, in the moister Douglas-fir region on the west slopes of the Cascade Mountains, recent research highlights the widespread role of non-stand-replacing fire in the structural development of some old forests (e.g., Tepley et al. 2013, Merschel 2021, Merschel et al. 2023), and this emerging understanding will be important to integrate into fire refugia science, forest conservation, and adaption to climate change.

Locations that remain unburned throughout their successional sequence are a classic example of fire refugia. The fire refugia concept presented by Camp et al. (1997) focused on truly unburned locations that developed closed canopy, late-successional forest in pre-colonization conditions of the Swauk Late-Successional Reserve (LSR) in the Okanogan-Wenatchee National Forest. Camp et al. (1997) recognized the historically frequent fire context of their work and were specifically looking for locations where fire flow was interrupted by biophysical conditions of the stand. Overall, the tree structure and microclimate (Chen et al. 1993) within many older, closed canopy Douglas-fir dominated forests appear to moderate fire behavior, particularly in core areas of old-growth away from forest edges (Lesmeister et al. 2021). Accordingly, identifying the geography of mature and old-growth forests that are more likely to persist into the future as fire refugia with a hands-off approach based on their inherent fire-resistant "asbestos forest" qualities, versus those that would benefit from vegetation management or underburning within or around them to make them more durable and restoring their ecological value, is a critical task for scientists, forest managers, and society.

Figure 1. Fire refugia are locations that burn less severely, or less frequently, than the surrounding landscape. This photo shows the position of fire refugia in complex terrain in a multiple use landscape, within the Holiday Farm 2020 fire footprint, Oregon.

In ecosystems of the moist, dry, and cold forests of the Pacific Northwest and the Northwest Forest Plan area (a.k.a. the range of the Northern Spotted Owl (*Strix occidentalis caurina*), hereafter NSO), fire refugia in mature and old-growth forests contribute important heterogeneity and ecosystem services through the structure and composition of forest stands. Fire refugia can align with the complex old forest structure preferred by NSOs as nesting and roosting habitat, and topographic position is increasingly recognized as an important component of that habitat (Camp et al. 1997; Lesmeister et al. 2021), for fire refugia (Meigs et al.

2020, Downing et al. 2021, Naficy et al. 2021), and old trees and forests (Keeton and Franklin 2004). But these dense, multi-storied closed canopy forests are increasingly vulnerable to high-intensity, stand-replacing fire, particularly under more extreme fire weather conditions (Kolden et al. 2017, Evers et al. 2022, WADNR 2022). Identifying whether there are locations more likely to persist through extreme events due to their topographic position or condition is critically important for old forest and NSO conservation, as is identification of mature forest stands that have a higher chance of surviving to old growth because of their condition, location, or landscape context.

Our challenge is to identify information on fire refugia pertinent to land management goals and tailored to the focal ecosystem. From this information we can develop an understanding of management actions that support the maintenance of sustainable fire refugia in mature and older forests - both closed canopy and open canopy - and recruit more mature and old-growth forest fire refugia that support our social and ecological values into the future. These goals are important at a project level (e.g., Little White Salmon Project area), the regional level (e.g., Northwest Forest Plan as a whole), and global adaptation of mature and old forests nationally and internationally (e.g., Executive Order 14072) to meet expectations of sustainable forest ecosystem services (e.g., biodiversity, carbon, water, economic, aesthetic and spiritual) into the future.

2. What products are currently available to map fire refugia in the region?

Research on fire refugia in forests of the Pacific Northwest has demonstrated predictable drivers of their occurrence with a variety of methods. In the last five years, numerous fire refugia products have been developed across the PNW region using contemporary remotely sensed data. We focus on two regional products: 1) holistic fire refugia models (Naficy et al. 2021, Naficy et al. in prep.), 2) topo-climatic fire refugia models (Yang et al. in prep). Additional related products provide complementary information related to fire refugia. For example, in the State of Washington the Large Dense Forest Sustainability models from WA DNR (www.dnr.wa.gov/ForestHealthPlan), provide information on relative fire risk and drought vulnerability for locations with medium and large trees. Additionally, information from tree ring studies of fire history (dendroecological data) from the last 800 years are becoming more broadly available and integrating fire refugia concepts (Merschel 2021; Merschel et al. 2023) and though the methods do not yet produce wall-to-wall mapped products, they complement findings from analyses of fire refugia from contemporary data and provide a deeper historical perspective for management decisions. Work by Camp et al. (1997) on closed canopy late-successional fire refugia provides an anchor for fire refugia science in the region, however the study itself covers a limited geographic area, mapping the 47 000 ha Swauk LSR. Camp et al. (1997) key in on the topographic template as a strong driver of fire refugia occurrence, identifying combinations of aspect, slope, elevation, and topographic setting predicting complex late-successional old forest fire refugia as identified by dendroecological methods.

The following summary describes the 1) holistic fire refugia, and 2) topo-climatic fire refugia products along with brief context to help forest practitioners understand the intent, value, and potential trade-offs and complementarities of each product.

1) Holistic fire refugia. This product was developed by researchers at Oregon State University in collaboration with USFS and USGS collaborators as a product from the Fire Refugia in Mature and Old Forests project. The goal of the work is to model the conditional probability of contemporary fire refugia and severity across the Northwest Forest Plan and Bioregional Assessment areas using explanatory variables representing all sides of the fire behavior triangle, including: topography, fire weather, fuels/vegetation (following general methods illustrated in Meigs et al. 2020 and Naficy et al. 2021). The model suite also include a variable representing rate of fire growth to distinguish between outcomes from “normal” fire spread events versus “blow up” events. The Eco-Vis map tool is valuable for understanding the particular drivers of fire refugia probability at any given location and examining the geography of fire refugia. Models and maps of the likelihood of fire refugia, moderate-severity fire, and high-severity fire are available for the NWFP region; the high-severity fire models are typically inverse of fire refugia, and all are available through Eco-Vis. While individual trees as fire refugia, and small clusters of these important living legacies often occur within locations characterized as having burned at moderate and high severity (Walker et al. 2019), we suggest focusing on the fire refugia models for identifying locations of more contiguous fire refugia qualities (<10% basal area loss from fire) at the 30-m pixel scale.

The fire refugia mapped products represent the relative probability of fire refugia occurrence - scaled from 0 to 100 - if a fire were to occur, given the topographic template, vegetation characteristics of the pixel (or site), and fire weather/fire growth. What we have learned from this research is that weather and fire growth context strongly influence fire refugia outcomes, and accordingly the user is required to select weather and fire spread scenarios of interest. The "fire weather" scenarios include: benign (10th percentile (*p*10W) of relative humidity and maximum temperature), moderate (*p*50W), and high (*p*90W) conditions for generating fire refugia probability. The "fire weather and fire growth" scenarios include the same fire weather variables plus a fire growth (FG) term in the same three scenarios (*p*10WFG, *p*50WFG, *p*90WFG). Figure 2 illustrates a map of the holistic fire refugia *p*50 "weather" scenario (holistic *p*50W) mapped for the Little White Salmon Forest Resilience and Wildfire Risk Mitigation Project on the Gifford Pinchot National Forest. Note, models were developed independently for two ecoregions: the moister, less fire-prone region and the drier, more fire-prone ecoregion and are stitched together to provide seamless coverage that includes expressions of closed canopy and open canopy fire refugia. Also, because models were fit across the entire forest region including very young stands post-disturbance, some of those young stands also support fire refugia qualities due to their low fuel abundance (low biomass values). These features are presented transparently in Eco-Vis. Overall, it is important to emphasize that the relative difference in values is what is most important for interpreting the predicted values of fire refugia, rather than focusing on absolute values.

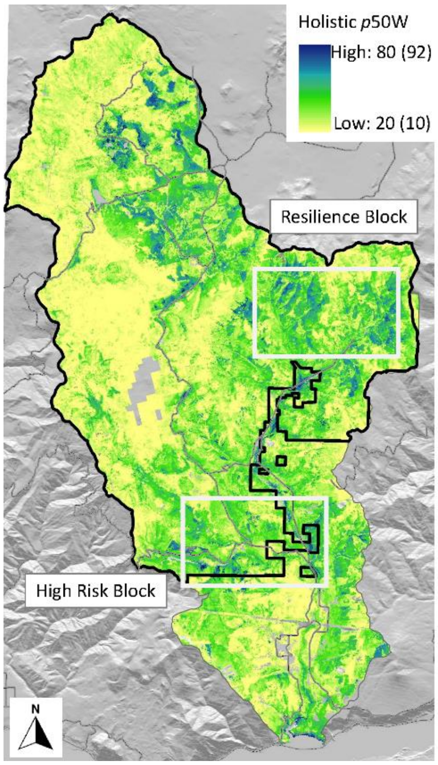

Figure 2. Map of the Little White Salmon Forest Resiliency and Fire Risk Mitigation Project and surrounding and encompassing watershed illustrating the geography of values for the holistic fire refugia *p*50W (weather scenario) model prediction map. Two inset boxes show selected areas with different goals within the project area: the Resilience Block in the northeast focuses on resilience and ecology, and the High Risk Block in the south focuses on ideas of fuels reduction and community risk reduction. *See section 8 for additional high resolution maps and an Avenza archive to support investigation of fire refugia in the field.*

Project teams can identify the scenario, or set of scenarios, they are interested in for different goals, and use those map layers for exploration, assessment, and planning. For climate change projections, the *p*90 scenarios for fire weather (W) and/or weather and fire growth (WFG) provide information on plausible future fire environment, given our understanding of climate change projections for mid-century (e.g., 2050). For management scenarios considering prescribed fire or wildland fire for resource benefit, the *p*10 and *p*50 scenarios provide plausible outcomes of burning under more moderate conditions.

Spatial resolution of the models is 30 m (Landsat remote sensing data), and models for both the moist and dry ecoregions were trained using fire data for 2002 to 2017 and validated on fires from 2020 and 2021 (described in Naficy et al. 2021). Current map products use 2017 vegetation conditions based on Gradient Nearest Neighbor (GNN) imputation maps, and some areas disturbed since that time may show refugia values different from current conditions. Fire refugia maps are currently being updated to 2022 GNN forest conditions and will be updated over time. Current data sets are available on the USFS T:/ drive, downloadable from the project website, and available in the Fire Refugia ToolBox (preferred) folder listed in section 8 (Additional Resources). Additional information can be found on the Fire Refugia in Mature and Old Forests website.

2) Topo-climatic fire refugia. This product was developed by Ray Davis and Zhiqiang Yang (USFS) and Andrew Yost (ODF). The goal of the work was to model the probability of potential fire refugia across the Northwest Forest Plan and Bioregional Assessment areas using four topographic variables and conditioned on climate (normal fire environment from Davis et al. (2017) as explanatory variables. The topo-climatic fire refugia model does not include variability in vegetation/fuels as a driver of fire refugia, instead using a simple mask of forest-capable sites to represent the intrinsic underlying condition. Accordingly, it should be overlaid with existing forest conditions to identify contemporary opportunities for supporting mature and older forest. In addition, this model provides the

opportunity to identify where on the landscape might be good locations to recruit high quality mature and old late-successional closed canopy forest, even if such conditions do not currently occur. The climate change projections from the model may identify locations most likely to persist as fire refugia into the future. The models prioritize a focus on the closed canopy late-successional, complex older forest context.

The topo-climatic fire refugia model is trained using multiple samples from contemporary fire severity data from the region (1985 to 2019), first building a model for probability of low-severity fire, next building a model for probability of high-severity fire, then aggregating the models together with the normal fire environment metric to generate fire refugia probability (Yang et al. in prep). Because the topo-climatic fire refugia models include the Davis et al. (2017) fire environment as an explanatory variable, the climate change projections from that work were fed in as scenarios for current period (2020), mid-century (2060), and late century (2100) climate change estimates. Spatial resolution of the models is 90 m (aggregated Landsat remote sensing data). Data sets are available on the USFS T:/drive and available in the Fire Refugia ToolBox (preferred) folder listed in section 8 (Additional Resources). Additional information will be provided in Yang et al. (in prep) and on the Fire Refugia in Mature and Old Forests website.

3. What are the drivers of fire refugia?

The geospatial drivers of the most sustainable fire refugia locations for the two model are described below:

1) Holistic fire refugia. The top-ranked variables in the holistic fire refugia models indicate vegetation/fuels and topographic template are both key drivers. Among all models, fire refugia probability consistently increases at higher levels of biomass (consistent with older forest stands), increases with greater composition of fire-resistant species, increases with either low (<25%) or high (>75%) canopy cover, and increases at lower topographic positions (consistent with valley bottoms, toe slopes, riparian zones). The lower canopy cover characterization is consistent with open forest conditions supporting fire refugia in drier positions of forest landscapes, and for moister forests high biomass closed canopies and constituent microclimate is consistent with supporting fire refugia. A challenge for management is determining where on the landscape we should select for closed canopy and open canopy fire refugia -- and this is where our fire refugia models aim to help. These are multivariable models, so that each location has a recipe for fire refugia that includes contribution from all variables, and each location on a landscape contains a unique mixture of those values. The response functions for the "fire weather" and the "fire weather and fire growth" models are illustrated in Appendix 1 and can be explored in more detail using the Eco-Vis Model Inspection Window (MIW) online tool. Figure 3 and Appendix 2 illustrate Eco-Vis.

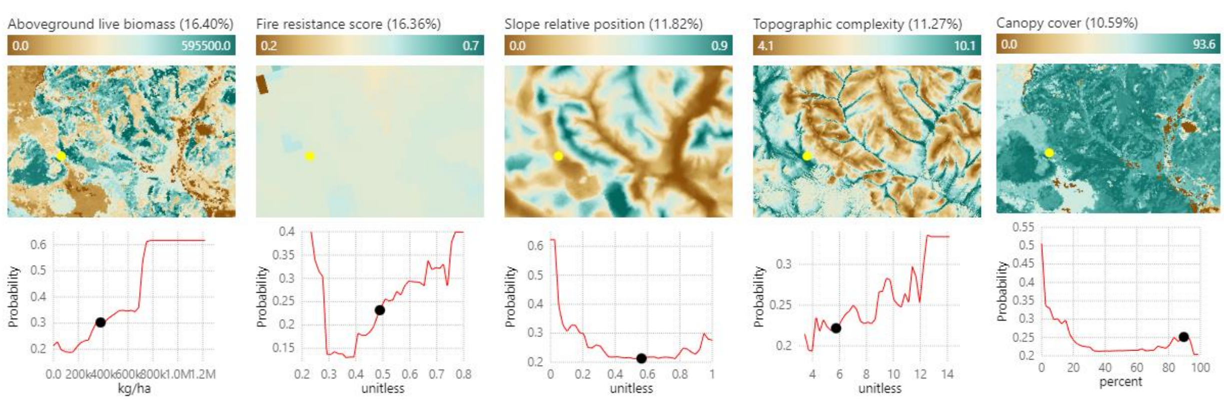

Figure 3. The Eco-Vis Model Inspection Window (MIW) provides an interface for understanding the drivers of fire refugia probability at any particular location. The user can use these response curves to see where the location "sits" in model space, to determine what factors are likely the most influential. For example, a small decrease in canopy cover at this location (yellow dot in map panels, black dot in response curves) would decrease fire refugia probability, all else being equal in the model. At lower values of canopy cover, a further decrease in canopy cover (e.g., from 40% to 20%) could increase the probability of fire refugia. This panel shows response curves for models of the "non-fire-prone", moister ecoregion. Only the top five variables in the model are shown here. Appendix 2 illustrates Eco-Vis in more detail.

For the dynamic elements of the models that contribute to generating the benign (*p*10), moderate (*p*50), and extreme (*p*90) map scenarios, daily fire growth (fire spread) was always a top explanatory variable, indicating that fire refugia probability strongly depends on rate of growth and that fire refugia are more likely to occur when fire is moving more slowly ("normal" fire growth) than more quickly (extreme or "blow up" fire growth). Maximum daily temperature and minimum daily relative humidity were generally the key weather variables, with probability of fire refugia decreasing at high temperatures and at lower relative humidity.

<u>2) Topo-climatic fire refugia.</u> The topo-climatic fire refugia models include four topography variables (from Theobold et al. 2015) and one fire climate variable (fire environment from Davis et al. 2017). Variables include: continuous heat-insolation load index (CHILI) representing cooler to warmer topography based on exposure to sunlight, adjusted to latitude; multiscale topographic position index (mTPI) representing a continuous index from drier (ridges) to moister (valley bottoms); physiographic diversity (physiodiversity) representing multi-scale diversity of geologic lithology with the land form; topographic diversity representing the variety of temperature and moisture conditions; and fire environment representing climatological "normal" of fire-proneness. Details can be found in Yang et al. (in prep), and response functions are illustrated in Appendix 3. Topo-climatic fire refugia probability generally increases with low and high levels of CHILI, lower levels of mTPI, lower levels of physiodiversity, higher levels of topodiversity, and both lower and higher ends of fire environment (fire climate) . Overall, fire refugia are predicted to occur in cooler, moister conditions supported by diverse topographic patterns (e.g., dendritic) in the more fire-prone areas, and topography seems to matter less when broad cool/moist conditions prevail (e.g., a coastal maritime influence).

4. Where are fire refugia located in the Little White Salmon project area?

The Little White Salmon Forest Resilience and Wildfire Risk Mitigation Project (hereafter LWS project) sits within the Mt. Adams Ranger District on the Gifford Pinchot National Forest of Washington State. The LWS project is a USFS planning area covering approximately 68,660 acres of the Little White Salmon watershed and is considered a transitional landscape that includes dry and moist mixed-conifer forest types in the eastern portion, and moister-cooler silver fir, mountain hemlock, and sub-alpine parkland forest types in the west and at upper elevations. The Scoping Document for the Project (April 2023) outlines threats to forest health and resiliency, wildfire risk, and old-growth habitat vulnerability, as three of ten key influences motivating management decisions. Figure 2 shows areas of the LWS area where forest resilience is the priority goal (Resilience Block), and where stand activities aimed toward the reduction of fire hazard and risk to communities is the priority goal (High Risk Block). Figures 4 and 5 illustrate the geographic patterns provided by the holistic and topo-climatic fire models to identify the locations where fire refugia are predicted to occur within the LWS area. We include maps of the WA DNR Large Dense Forest Sustainability layer, for context, given familiarity of the manager group at LWS with this product.

For the <u>holistic fire refugia</u> products we used two scenarios most applicable to this project exercise (Figures 4 and 5). First, the holistic fire refugia *p*50W (weather) scenario provides maps of the relative probability of forest persistence under moderate levels of temperature and relative humidity in a fire season. This product shows expected outcomes under weather often experienced in our region during the fire season, outside of extreme spread event days. In section 8 (map resources) we illustrate the comparison of *p*50W (weather) against the *p*50WFG (weather and fire growth) scenario to show that under those moderate situations both scenarios show very similar patterns (note the same is true for benign *p*10W and *p*10WFG scenarios). The second scenario we show is the fire refugia *p*90W (weather) scenario, which shows a notable reduction in the probability for persistence under these extreme fire weather conditions. This *p*90W scenario would be appropriate for use as a climate change scenario for mid-century, with the expectation that large fires will be more likely to burn under warmer and drier conditions. We do not include the *p*90WFG (fire weather and fire growth) map here, which aims to illustrate likely outcome of extreme fire weather and extreme fire spread – the maps indicate very low fire refugia probability over the entire watershed with the exception of a few very small pockets of fire refugia; these maps are available in section 8.

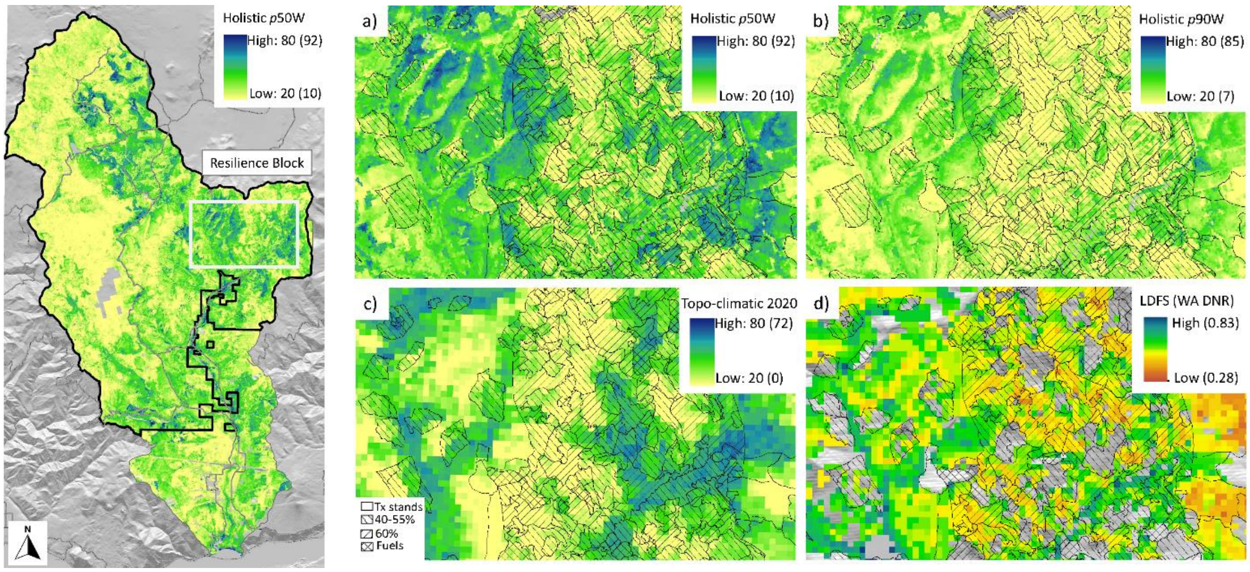

Figure 4. Maps of three fire refugia concepts for the Resilience Block of the Little White Salmon Project area. Proposed treatment stands are shown with black outlines in panels a-d, with proposed treatments illustrated as 40-55% cover, 60% cover, and Fuels treatments. We illustrate a) holistic *p*50W, b) holistic *p*90W, c) topo-climatic refugia 2020, and the layers use the same color ramp so that "Low" includes all values less than 20, "High" includes all values greater than 80, and the continuous ramp illustrates the range of intermediate values. We use parentheses () to identify the minimum and maximum observed values for each layer. Also shown for comparison is d) the WA DNR Large Dense Forest Sustainability layer. High resolution versions of maps are available in section 8 (fire refugia maps).

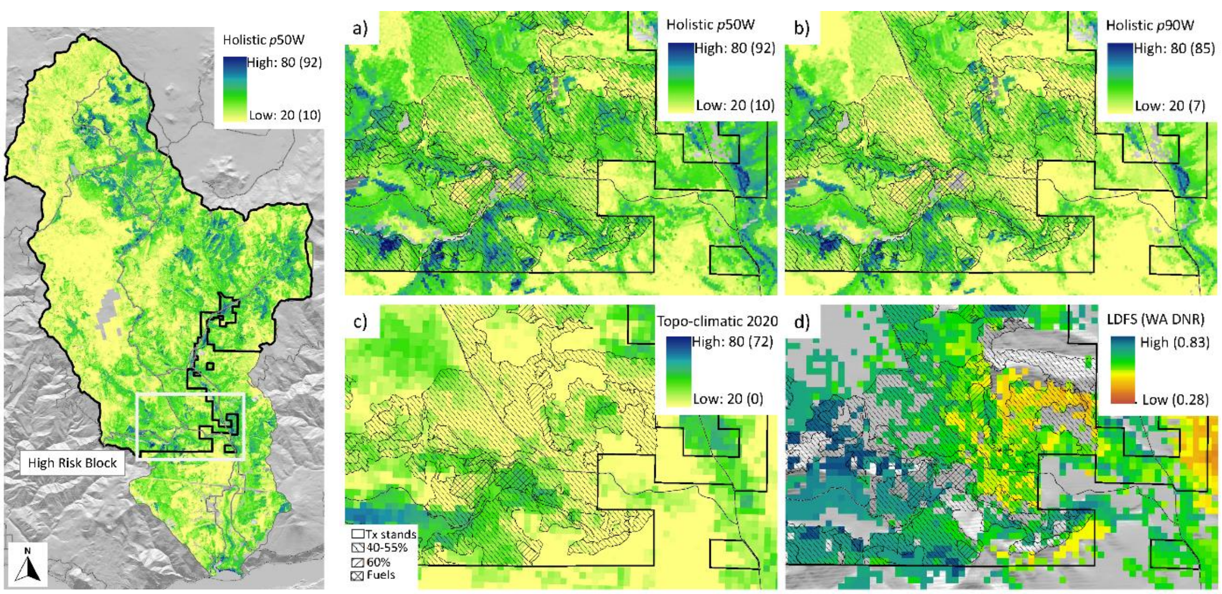

Figure 5. Maps of three fire refugia concepts for the High Risk Block of the Little White Salmon Project area. Proposed treatment stands are shown with black outlines in panels a-d, with proposed treatments illustrated as 40-55%, 60% and Fuels treatments. We illustrate a) holistic *p*50W, b) holistic *p*90W, c) topo-climatic refugia 2020, and layers use the same max/min color ramp so that "Low" includes all values less than 20, "High" includes all values greater than 80, and the graduated ramp in between illustrates the range of intermediate values. We use parentheses () to identify the minimum and maximum observed values for each layer. Also show is d) the DNR Large Dense Forest Sustainability layer. High resolution versions of maps are available in section 8 (fire refugia maps).

For the topo-climatic fire refugia products, we used one scenario most valuable for this project exercise (Figures 4 and 5): the topo-climatic 2020 scenario. The topo-climatic 2020 scenario shows the potential for fire refugia under normal fire environment characteristic of the current time period. The effect of terrain variables included in the models is clear in the dendritic patterns of refugia likelihood. Scenarios for future climates are illustrated in section 8, and in Figures 6 and 7. The topo-climatic 2060 scenario shows expected outcomes based on a GCM ensemble for climate projections of fire environment for mid-century (see Davis et al. 2017 for details on GCM ensemble approach). The topo-climatic 2100 scenario illustrates outcomes for end-of-century climate projections. A comparison of these scenarios shows how changes in the 30-year climatology of fire influences the potential for fire refugia. Overall, very little change is observable among the three scenarios (e.g., see Figure 6 and 7), so we focused on the 2020 scenario here. Choosing the 2060 scenario could be a logical choice to explicitly capture mid-century conditions.

The fire refugia concepts can be overlaid as templates, and interpreting the overlap provides important information for current and future management. We developed a set of examples for interpreting how information from the holistic fire refugia and topo-climatic fire refugia maps overlap (Table 1, Figure 6). Discussion of what management goals could be appropriate in different situations and interpretations is a topic for individual management teams, and we provide some ideas for that work in sections 6 and 7 (Frequently Asked Questions).

Table 1. Fire refugia product scenarios and interpretation of their overlap. The interpretations include ideas of current and future persistence and recruitment of fire refugia. Also included are basic interpretations of fire refugia and LDFS overlays. A reminder for holistic fire refugia: closed canopy moist forest, open canopy dry forest, and very young open canopy early seral with low fuel environments can all express as high fire refugia values. Superscripts [f,g,h] refer to panels in Figure 6.

Layer 1 description	Layer 2 description	General interpretation
HIGH holistic p50W	HIGH topo-climatic 2020	Fire refugia in suitable locale for current context
HIGH holistic p50W[f]	HIGH topo-climatic 2060	Fire refugia in suitable and durable future locale
HIGH holistic p90W[g]	HIGH topo-climatic 2060	Fire refugia in suitable and very durable future locale
HIGH holistic p50W	LOW topo-climatic 2020	Fire refugia in sensitive locale for current context
HIGH holistic p50W	LOW holistic p90W	Fire refugia in sensitive locale for future context
LOW holistic p50W	HIGH topo-climatic 2020	Potential near-term refugia with management
LOW holistic p50W[f]	HIGH topo-climatic 2060	Potential future refugia recruitment w/ management
LOW holistic p90W	HIGH topo-climatic 2060	Potential future refugia recruitment w/ management
MAX holistic p50W[h]	MAX topo-climatic 2020	HIGH MAX value of either layer in combination, suitable
HIGH holistic p50W	HIGH LDFS	Fire refugia in suitable and durable locale
HIGH holistic p50W	LOW LDFS	Fire refugia in locale supporting open dry refugia
LOW holistic p50W/p90W	HIGH LDFS	Uncertainty - integrate other highly valued resources

The interpretations provided in Table 1 provides a starting point for decision making. For example, overlays listed as “fire refugia in sensitive locale” point to places where vegetation management of existing stand conditions could improve fire refugia characteristics; whereas “potential… refugia recruitment with management” points to locations where succession and vegetation management could improve refugia characteristics. Overlays listed as “fire refugia in suitable and durable future locale” point to areas where limited or no management treatments might be needed to maintain high value fire refugia and forest qualities. Overlays with other highly valued resources (e.g., Figure 7) can provide additional information valuable to management decisions.

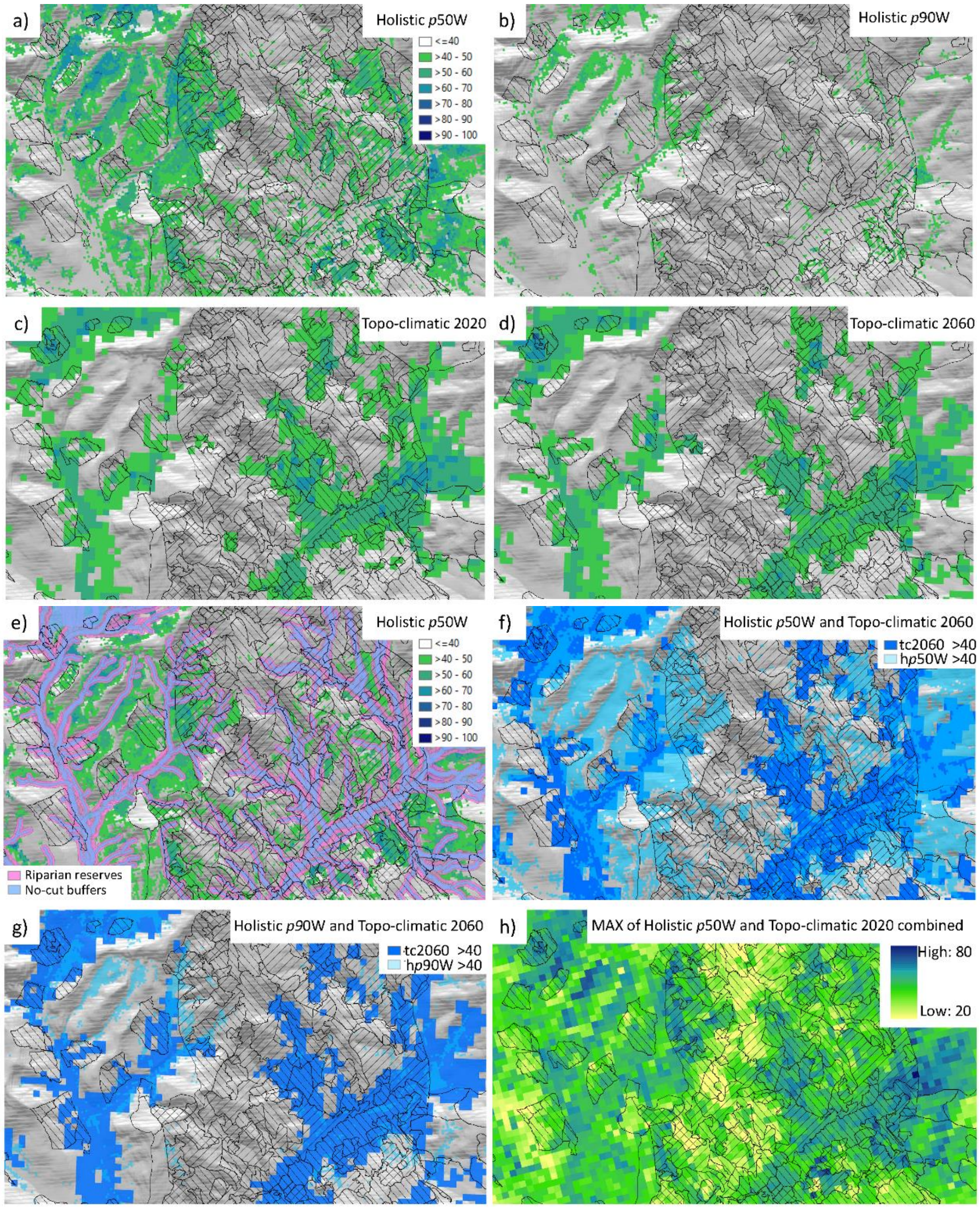

Figure 6. Templates of fire refugia can work together to identify locations of agreement, High rank, and Low rank conditions, as described in Table 1. a) Locations where fire refugia likelihood is predicted as moderate-high (>40) for the holistic *p*50W fire refugia model; b) locations predicted as moderate-high (>40) for the holistic *p*90W model; c) predicted as moderate-high (>40) for the topo-climatic 2020 climate scenario; d) predicted as moderate-high (>40) for the topo-climatic 2060 scenario. Comparison of panels c, d, and e illustrate that topo-climatic fire refugia are largely coincident with riparian zones. Panel e) shows holistic *p*50W fire refugia with riparian reserves and no-cut buffers illustrating that sometimes, but not always, holistic fire refugia occur in riparian zones. Panel f) illustrates an overlay of HIGH holistic p50W and HIGH topo-climatic 2060 fire refugia values that show fire refugia in suitable and durable future locales; also, locations with LOW holistic p50W and HIGH topo-climatic 2060 could be locales for potential future refugia recruitment with vegetation management. Panel g) shows a similar scenario to f) but using HIGH values of the holistic p90W and topo-climatic 2060 models to identify fire refugia in suitable and *very* durable future locales. Panel h) shows values where the Maximum value for a pixel, from either the holistic p50W or topo-climatic 2020 models shows a combined fire refugia surface integrating both products. Overall, a cut-off value of >40 was selected to represent moderate-high values; others could be used. Further information for management can be obtained using the Eco-Vis tool (e.g., Appendix 2) and overlaying fire refugia maps with other highly valued resources (e.g., Figure 7). High resolution versions of maps are available in section 8 (fire refugia maps).

5. How do fire refugia overlap with other highly valued resources in the LWS project area?

Understanding how holistic fire refugia and topo-climatic fire refugia overlap with other highly values resources provides information to interpret refugia layers in a broader context, and identify potential management actions. Overlays with other resources helps us understand what makes a given dataset unique, as well as opportunities to use datasets in tandem to add value. With the wide range of mapped products available for resource management, identifying similarities and distinctions among layers helps to identify uses and answer the question "which tool should I use for my project if I want to know… xxxx"? This idea is revisited in the next two sections, using a Frequently Asked Questions approach.

There are a wide variety of layers to consider in overlay analysis to meet management needs, including:

- Time series of modelled, predicted habitat for northern spotted owls showing ephemeral and persistent habitat locations that point to fire refugia *from* high-severity fire *for* owls (Davis et al. 2022a)
- Old-Growth Structural Index at different levels (e.g., OGSI80 and OGSI200; (Davis et al. 2022b)
- Strategic fire management outputs including from Quantitative Wildfire Risk Assessment, PODs, PCLs.
- Integrated prioritization products such as WA-DNR Large Dense Forest Sustainability, dual benefit, and component layers.
- Land use allocations, riparian reserves, and accessibility.

Figure 7 provides an example of overlay analysis using OGSI200 and OGSI80 maps.

6. What do fire refugia models tell us about management at the stand and watershed scale?

This section uses a Frequently Asked Questions (FAQ) approach to provide information on using fire refugia products for management. The questions and responses were developed by Meg Krawchuk (OSU), Garrett Meigs (WA DNR), Jessica Hudec (USFS-Ecology Program), and Blake Murphy (USFS-GPNF). The FAQ do not represent prescriptive or comprehensive coverage of the information. The goal of the FAQ is to start a conversation on ideas based on academic and management expertise, and for these FAQs to evolve into ongoing discussions related to use of fire refugia data products to inform vegetation management decisions.

Stand scale:

Q1. From a management perspective, what does it mean when fire refugia values are high? Locations where *holistic fire refugia* probabilities are high point to locales where minimal stand treatment may be needed for sustaining existing forest conditions, in terms of hazard from stand-replacing wildfire. In moister landscape positions these could be locales where thinning the canopy could disrupt microclimates developing in mature forests, as long as existing vegetation structure is relatively fire resistant, and topographic position is supportive of disturbance refugia (e.g., through higher water balance, fuels composition and structure, and/or terrain position). Underburning and some understory thinning might still be warranted in or around these stands, given our increasing recognition from dendroecology/fire history studies of the integral role of low-severity surface fire activity in forests of the western Cascades. In drier landscape positions, high fire refugia values could point to locales where more open stand conditions exist and must be maintained to preserve fire refugia characteristics. Where *topo-climatic fire refugia* values are high, this points to locales where terrain and climate are likely to be more supportive of fire refugia – recruitment of high quality mature and old-growth forests might be a priority for these locations, even with a low *holistic fire refugia* value driven by current forest structure or composition -- see Table 1 and Figures 6 and 7 to think through situations where topo-climatic fire refugia and holistic fire refugia information in tandem provide important details for management.

Q2. How can I use the Eco-Vis tool to interpret fire refugia values in a management context? Using the Eco-Vis tool that accompanies the *holistic fire refugia* and severity modelling suite can provide insights into how management in particular stands might affect fire refugia probability values for those stands, by allowing the user to tailor their assessment to the specific multi-variate biophysical context of the locale. For example, terrain features play a prominent role in driving the probability of fire refugia, so a vegetation management activity would be expected to have different outcomes depending on the terrain position of the site. The primary vegetation variables driving the *holistic fire refugia* models are FRS (fire resistance traits of stand composition), biomass, and canopy cover. The

Eco-Vis tool allows a user to visually estimate how a change in any of these vegetation variables, through potential management actions, would affect fire refugia probability, i.e., if management would result in an increase, a decrease, or perhaps no change in the relative probability of a stand persisting as a fire refugium.

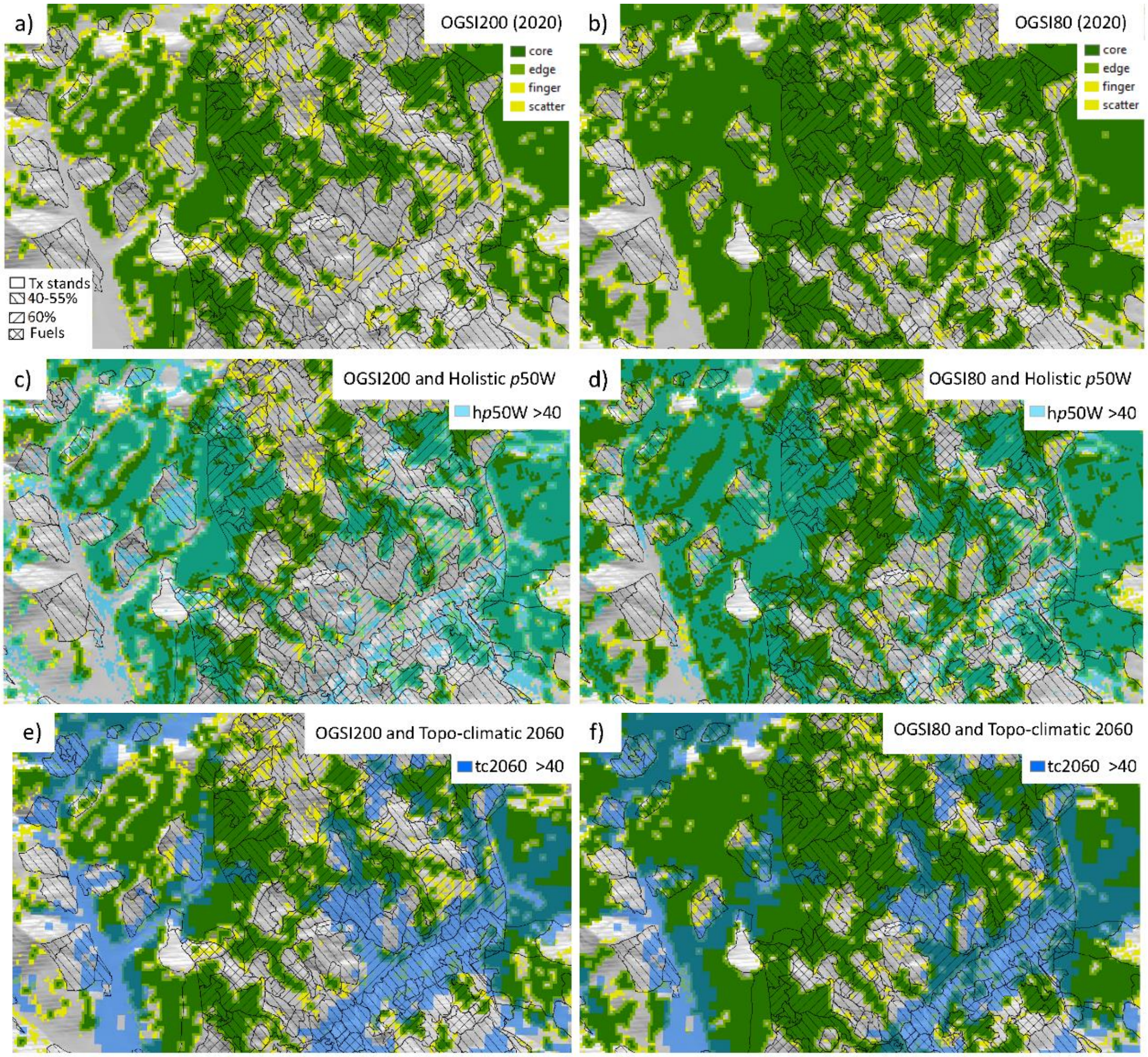

Figure 7. Templates of fire refugia can work with other data layers including highly valued resources, to further interpret fire refugia values and consider what they represent for ecosystem services. a) The Old Growth Structural Index for 200-year+ stand structure (OGSI 200) demonstrating areas of core, edge, finger, and scatter of old forest mapped by remote sensing and models. Areas of core OGSI may have the strongest fire refugia characteristics. b) The OGSI80 (80-year+ stand structure demonstrating areas of core, edge, finger, and scatter of mature and old forest. c) Overlay of OGSI200 and the holistic p50W fire refugia product >40 showing areas of old forest in locales with higher and lower chances of persistence as refugia through high-severity fire. d) Overlay of OGSI80 and holistic p50W >40 showing areas of mature and old forest (MOG) in locales with higher and lower chances of persistence through high-severity fire. Locations of OGSI200 or OGSI80 with low values of holistic p50W are places where vegetation management for fuels reduction and resilience might be warranted; these are likely upland areas where fire exclusion may have allowed for recruitment of older closed canopy forest in locations where more open forest conditions may have been common in the past and are important to consider for adaptation to future climates. These could also be areas where disturbance-succession cycles are bound to produce important early-seral conditions from high-severity fire given terrain position, i.e., steeper slopes. e) Locales where OGSI200 and high values of topo-climatic fire refugia 2060 overlap identify areas where old forest is most likely to persist; f) the same holds for OGSI80 for mature and old forest persistence. Locations where high values of topo-climatic 2060 occur without current OGSI200 or OGSI80 are areas where recruitment of mature and old forest could be prioritized to persist, and these locations of high value topo-climatic refugia potential are largely coincident with riparian zones. High resolution versions of maps are available in section 8 (fire refugia maps).

Q3. How might I use the Eco-Vis tool to analyze canopy cover retention criteria? What does this mean in drier versus moister systems? The canopy cover variable in the *holistic fire refugia* model provides a valuable tool for understanding how fire refugia may be sensitive to canopy cover retention criteria for any specific biophysical template. For a given locale, use the Eco-Vis "Model Inspection Window" (MIW) to assess where thresholds are crossed, relative to current conditions, resulting in distinct changes in fire refugia probability. The mapped fire refugia predictions are developed from models of two ecoregions: the moister, less fire-prone region and the drier, more fire-prone ecoregion (see page 5). Accordingly, the interpretation of the biophysical conditions that support fire refugia includes expressions of closed canopy and open canopy fire refugia, and moister and drier terrain locations. Understanding the variability in water balance and terrain template is critically important for making decisions about whether it is preferable to thin a stand to reduce crown fire susceptibility and encourage fire flow along the surface (dry forest concepts) versus leave it alone and let the microclimate and fuels complex dampen fire flow and crown fire susceptibility (moist forest concepts).

Q4. What do I do when I see fire refugia values are heterogeneous within a stand? Refugia values may vary within stands due to variation in topography, forest conditions, and/or weather. The within-stand detail can help you develop potential treatments, suggesting best locales for certain prescriptions, e.g., skips and gaps or prescribed burning. For some smaller stands, a weighted average or majority filter of fire refugia values could be useful for providing general refugia characteristics. As with any data product, the most important piece is to be clear and transparent with its use and interpretation in the context of resource objectives.

Q5. How do I develop an intuition and understanding for the fire refugia maps and drivers, given the look and feel of what I see in the forest? You can bring a map of the fire refugia products out to the field in Avenza or FieldMaps, do a stand exam/cruise it, and note the terrain conditions. Then back at the office use Eco-Vis to examine the influence of different variables on fire refugia probability and cross-walk your stand exam data to the vegetation variables in the model to help understand why that location has a particular *holistic fire refugia* value.

Q6. The vegetation data in the models are based on the GNN model product, and I have some concerns about uncertainty in that mapped product. How should I approach that uncertainty? What is the finest scale at which I should use fire refugia data? Even though GNN maps include uncertainty in the mapping of forest conditions, we see interpretable patterns and logical relationships with vegetation/fuels variables in the fire refugia models, which gives us confidence that the outcomes are robust. Also, the GNN variables that provide the strongest prediction in the models (FRS, biomass, canopy cover) are variables that have relatively high correlation to observed field-measured values in GNN validation tests. However, for any given site or stand, there may be discrepancies between the GNN values and observed stand conditions at a fine scale on the ground. The *holistic fire refugia* models are developed at a 30-m resolution, and we suggest using pixels and their neighbors (9 pixel set) to characterize their quality for best results. Also, stand exam or plot data from field visits can help interpret or verify values provided by GNN.

Q7. How does managing with fire refugia in mind align with other objectives? E.g., old growth, owls, fire and fuels, riparian zones. As illustrated in section 5, overlays of fire refugia data with other objectives or highly valued resources provides information can inform management decisions. In Figure 7, we see where OGSI200 (old-growth forest) overlaps with low *holistic fire refugia* value, suggesting areas where current old-growth forest may have high vulnerability to stand-replacing fire. From an old growth conservation and adaptation perspective, this information could suggest how vegetation management in or around that old-growth forest stand might make it more durable to high-severity fire. Using Table 1, Figures 6 and 7, and overlays with other highly valued resources provides an invitation to discuss complex local management objectives. There is no one size fits all prescription, however lessons learned from conversations among managers will provide a rich resource of ideas and considerations moving forward.

Watershed/landscape scale:

Q8. Can I use the fire refugia products to identify where to treat on a landscape? Yes, ideally you can use components of fire refugia as a driver to identify where to treat on a landscape, and to inform proposed actions in stands that have already been identified for treatment based on other information or processes/objectives. For example, in the LWS project, treatment stands were identified *a priori*, and fire refugia products are being used to evaluate treatment locations and appropriate treatment prescriptions. However, on the Shasta-Trinity National Forest in northern California, fire refugia products were used to guide the identification of stands to be treated to contribute to an ongoing discussion of a "fire refugia alternative".

Q9. What can I learn by using model overlays to visualize fire refugia across the landscape and over time and in the context of changing climate? As illustrated in Table 1 and Figure 6, there are a variety of interpretations that come from overlays of fire refugia products. *Holistic fire refugia* probability values in some locales decrease as fire weather and fire growth conditions ramp up, illustrating a sensitivity to climate change and the more extreme conditions expected for the future. For *topo-climatic fire refugia*, the models are driven by climate projections and explicitly include predictions for the years 2020, 2060, and 2100. Intentional mapping of the holistic and topo-climatic fire refugia products point to locations that have a higher chance of being durable, and locations that may be ideal areas for recruitment of forests with high fire refugia value into the future.

Q10. How do fire refugia products relate to QWRA data and PODs? This is an important question that needs to be explored more fully. Each product includes its own assumptions and uncertainties. For example, fire risk maps and the PODs approach could be considered a fire management-oriented version of fire refugia (i.e., identifying locations with relatively low crown fire risk or where fire can be allowed to burn for resource benefit), but with their own decision frameworks. Integration of PODs and fire refugia models would be an interesting topic for a future workshop. Fire probability and conditional flame length from fire simulation models contributing to the QWRA modelling framework have very specific definitions, some of which align with fire refugia concepts very easily and others not. Old forests with high fire refugia values are considered in upcoming QWRA products. Further examination of the relationships between products from fire refugia models and fire behavior simulations will be important for understanding the geography of forest persistence into the future.

Q11. What actions are appropriate when an area of high fire refugia probability falls along a PCL, in the context of strategic fire management? Overlays of fire refugia data with strategic fire management products like Potential Control Lines (PCLs) and PODs provide information that, considered in tandem, can inform management decisions. E.g., in moist forests, if both the *holistic fire refugia* and *topo-climatic* rating are high, manipulation of the stand is likely to alter microclimate and decrease refugial probability. This might be an area to "skip" in hazard treatment, relying on inherent fire behavior-reducing characteristics of the patch to enhance the effectiveness of the PCL without additional treatment. A buffer from adjacent treatments may be merited depending on patch size. If the holistic fire refugia probability is high but topo-climatic refugia probability is low, this area might be at greater risk of fire, and the case for understory removal to enhance the effectiveness of the PCL would be stronger, as this area is more prone to high-severity fire and less likely to provide durable fire refugia into the future. The decision-maker will ultimately have to consider the cost/benefit of treatments for different objectives; fire refugia models can help inform that cost/benefit analysis.

Q12. Would I manage differently according to patch sizes of fire refugia? This question, as with the others, would need to be tailored to a particular place. What we do know is that for many of our older forests, edge effects seem to be eroding the capacity of moister forests to dampen fire (e.g., Lesmeister et al. (2021) show an edge effect for NSO habitat and high-severity fire). And recent observed fire severity is greater in edges and islands than it is in "core" areas of old (OGSI200) forest (R. Davis pers. obs.). Accordingly, larger "core" patches of old forest are more likely to persist as fire refugia than are core-edges, fingers, and scattered islands (e.g., <2.5 acres). Since the *holistic fire refugia* models do not include explicit information about whether a pixel is part of a patch of fire refugia, versus isolated, we need to use ancillary information to make decisions about how to manage in the context of patch size. Figure 7 illustrates these concepts. Note, Camp et al. (1997) comment that high levels of forest connectivity could be a potential negative for crown-fire flow, so that clumps of core areas may be beneficial, but large swaths of continuous forest may be detrimental. This speaks to maintaining appropriate levels and scales of landscape heterogeneity, an important topic for future work.

7. How could forest management increase the extent and sustainability of refugia?

Q13. How could fire refugia models and other overlay maps inform treatments in the LWS project area, in priority landscape locations and types, across the range of the Northwest Forest Plan, and beyond? This manager's brief provides initial guidance for integrating fire refugia maps into management decisions by demonstrating overlays, interpretations (e.g., Table 1, Figure 6, 7), and tools (e.g., Eco-Vis) for decision support. Interdisciplinary team members working on the LWS project are using fire refugia models to explore the best treatment options along PCLs; identify canopy cover retention thresholds that influence refugia probability, particularly in areas of higher habitat quality for NSO and riparian reserves; and explore treatment layout options, including locations of skips and gaps. Fire refugia concepts and mapping are also being integrated into re-thinking guidelines for Late-Successional Reserves in dry forest settings, contributing to thinking about potential ideas for the Late-Successional Reserve network and concepts within the NWFP (Old Forest Assessment), and could contribute to understanding vulnerability of mature and old-growth forests mapped and defined under President Biden's Executive Order 14072.

Q14. What can we do with the holistic fire refugia scenarios to address climate change? Due to the east-west transitional geographic position of the Little White Salmon project area along the crest of the Cascades in the Gifford Pinchot National Forest, particularly in the context of climate change, the dynamics of dry, moist, and cold forest ecology need to be a part of the conversation. The *holistic fire refugia* models include the *p*90 scenarios, which represent weather and fire conditions expected to become more common with climate change. The *p*90W models include 90th percentile weather conditions, and the *p*90WFG include 90th percentile weather and fire growth conditions. Using these high-percentile model outputs can provide likely scenarios for future fire. The *topo-climatic refugia* future (2040 and 2060) scenarios can provide information driven explicitly by GCM projections and point to locations most likely to provide "hang time" for existing fire refugia, or locations well-suited to recruit forests with greater durability into the future. Ongoing discussions should also include wildland fire for resource benefit (managed wildfire) and prescribed fire in the context of using "beneficial fire" as climate changes. The *p*10W and *p*50W *holistic fire refugia* models provide a helpful tool for considering likely outcomes of wildfire under benign and moderate conditions most likely to be conducive to those management scenarios.

Q15. How do we use fire refugia models to determine how to create more refugia through silvicultural prescriptions? Locations where *holistic fire refugia* probabilities are low but *topo-climatic fire refugia* values are high (e.g., Table 1, Figure 6) point to locales where silviculture treatments could improve sustainability of forests and enhance refugial characteristics. Locations where holistic fire refugia probabilities are high but topo-climatic fire refugia value are low may point to "apparent refugia" that look like good quality mature or old-growth forest from the perspective of forest conditions but are in the wrong place (terrain position) to be maintained as refugia. These sites may need to be treated to maintain more of a drier, old-growth character. Additionally these stands could be in a terrain location (steep slopes) with a cycle to burn at high severity every 80-200 years, creating important early-seral conditions and heterogeneity. Key vegetation/fuels drivers of *holistic fire refugia* are biomass and canopy cover; we need to leverage these, and their interaction, to think through unique prescriptions across the landscape. The Eco-Vis tool that accompanies the *holistic fire refugia* and severity modelling suite can provide insights into how management in any stand or watershed might affect fire refugia by allowing the user to tailor assessments to the specific multi-variate biophysical context of that stand or watershed.

Q16. What do we do with fire refugia data in riparian areas given they have specific management needs and goals? Do treatment recommendations align? Under current forest practices, existing riparian strategies must be followed within riparian zones. It would be valuable to see how much of the overall high fire refugia value is located within designated riparian zones, compare *topo-climatic* and *holistic fire refugia* maps (e.g., Figure 6), and identify where riparian zones rank low according to fire refugia characteristics. Stream confluences and low slopes are logical and expected locations for fire refugia, but there may be some positions where higher fire severity should be expected. From a broader ecosystem perspective, it would be interesting to consider modifications to management activities can occur in riparian zones and adjacent uplands, using fire refugia products to inform that decision process.

8. Additional resources on fire refugia

The following resources can be accessed through links below and the shared **Fire Refugia ToolBox** folder:

Fire refugia in mature and old forests website: https://firerefugia.forestry.oregonstate.edu/ provides resources about fire refugia concepts, detailed methods for *holistic fire refugia* models, portal to Eco-Vis, including download for holistic fire refugia map products. Information on the *topo-climatic fire refugia* product will be added in Summer 2023.

Fire refugia maps and field maps archive: folder containing maps of fire refugia products illustrated in this manager's brief provided at high resolution, and including for field use in Avenza or FieldMaps

Library of literature resources: folder containing literature cited in the manager's brief, and related readings, infographic, and poster showcasing the holistic fire refugia and severity suite of products

Library of data resources: folder containing the holistic fire refugia and severity suite of map data, and the topo-climatic fire refugia map data products

Fire refugia webinars:
Links to short presentations from the 2023 Post-Fire Research and Monitoring Symposium with relevance to fire refugia -

- Merschel et al. (2023): "800 years of post-fire forest development data in west side Douglas-fir forests" [32:39-57:20 minutes]
- Krawchuk et al. (2023) "Fire refugia, old forests, & spotted owls" [5:31:50-5:59:50]

"Fire refugia: where and why do conifer forests persist through multiple fire events", presented by Meg Krawchuk as a webinar for the Forest Stewards Guild. Krawchuk, M.A. (2021)

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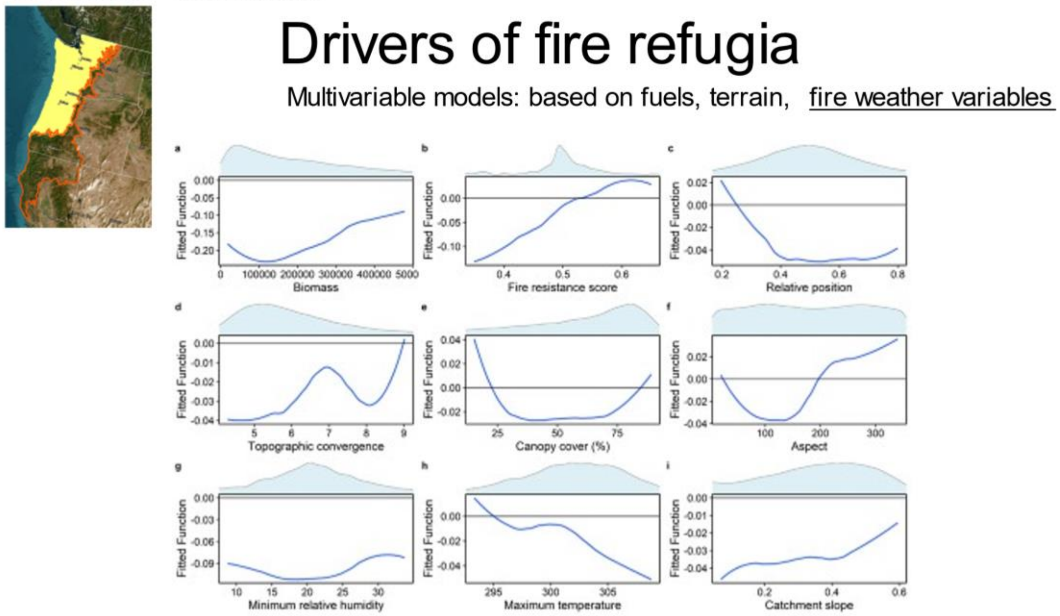
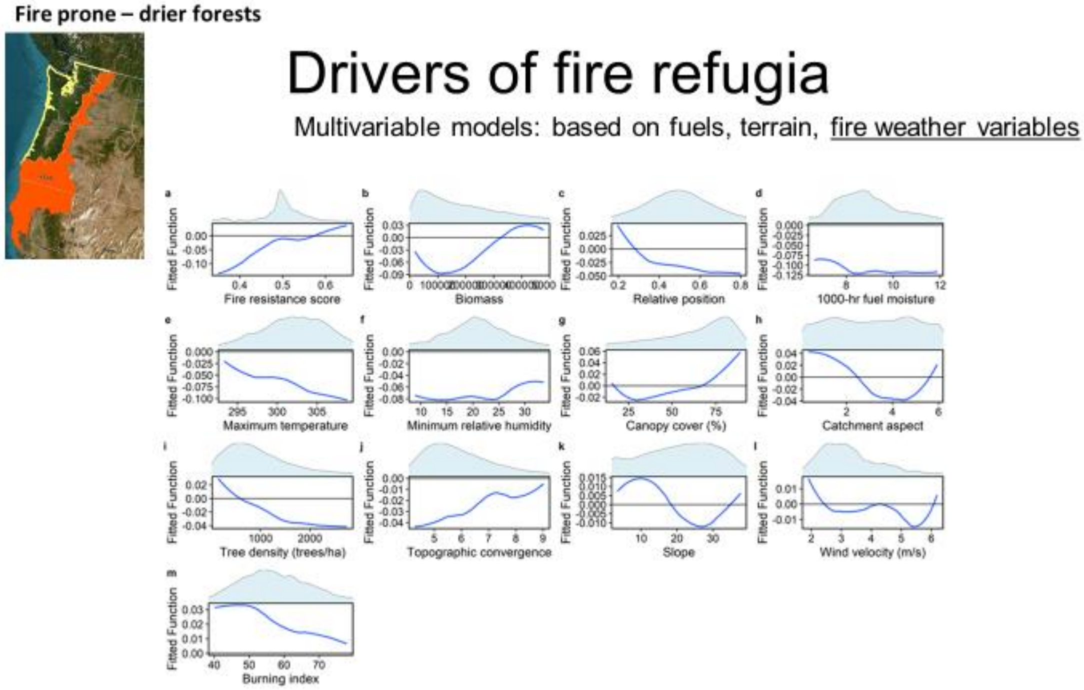
Appendix 1.

Response functions from holistic fire refugia models, from Naficy et al. (2021). See [Eco-Vis Model Inspection Window] online tool for more details.

Less fire prone – moister forests

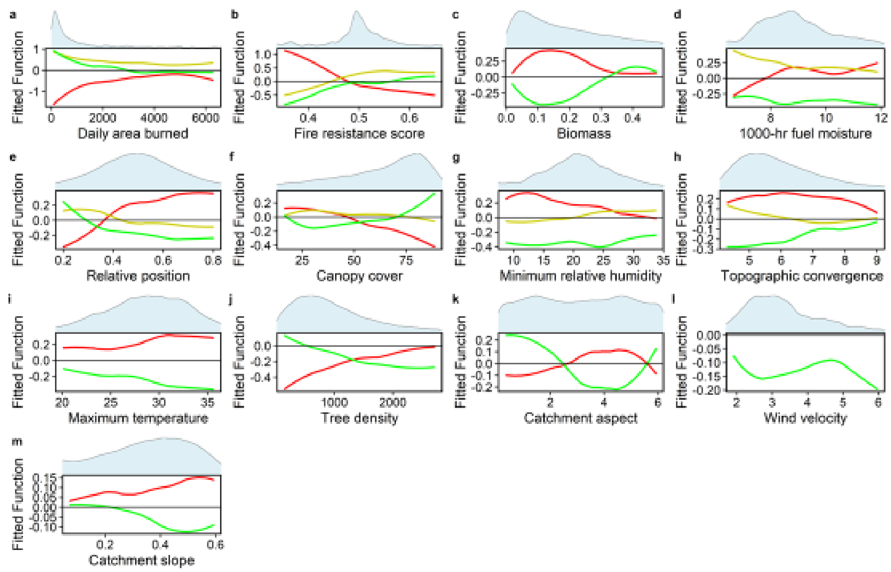


Fire prone – drier forests



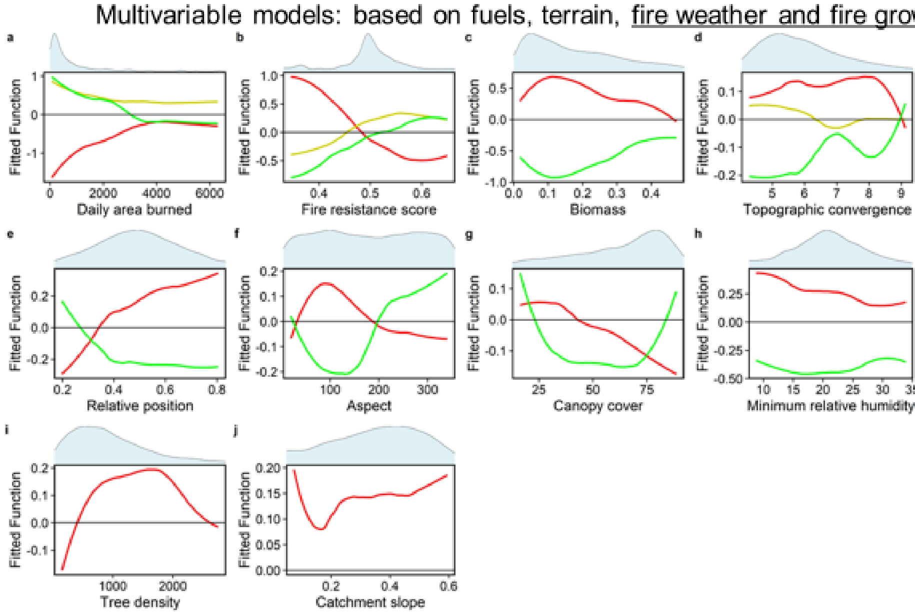
All severities: drier ecoregion

Multivariable models: based on fuels, terrain, fire weather and fire growth



All severities: moister ecoregion

Multivariable models: based on fuels, terrain, fire weather and fire growth



Appendix 2.

Screen-captures from the Eco-Vis webtool that provides users with opportunity to visualize the holistic fire refugia products under different fire weather and fire growth scenarios with an easy map-viewer (Figure 1), and examine the drivers of fire refugia probability for any given pixel using the Model Inspection Window (the MIW; Figure 2).

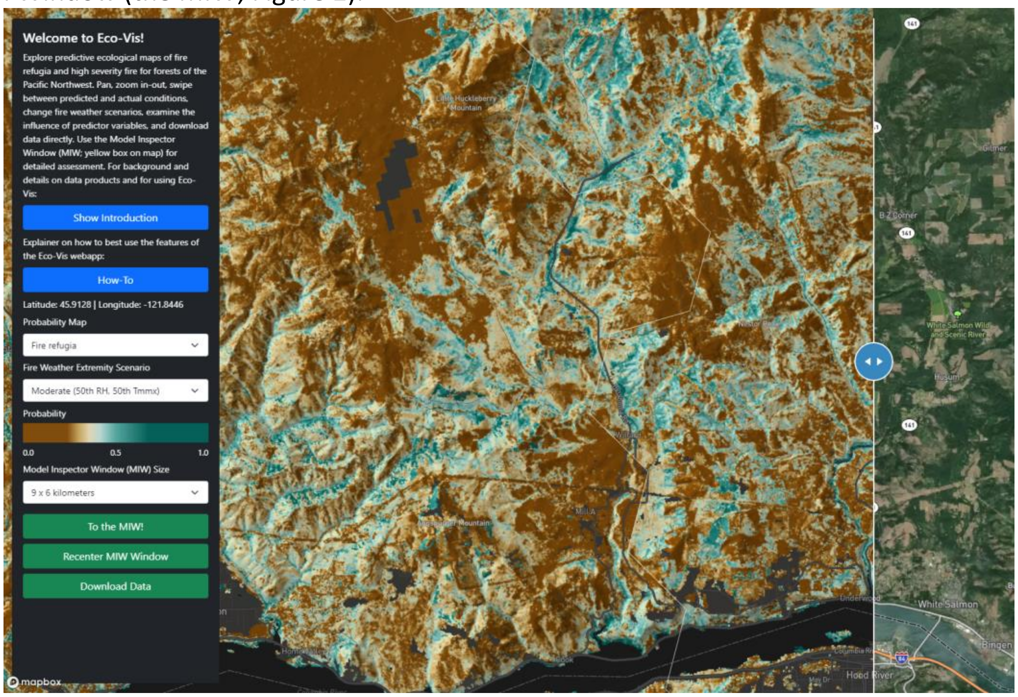


Figure 1. A screen-capture of the Little White Salmon project area showing the map-viewer in Eco-Vis.

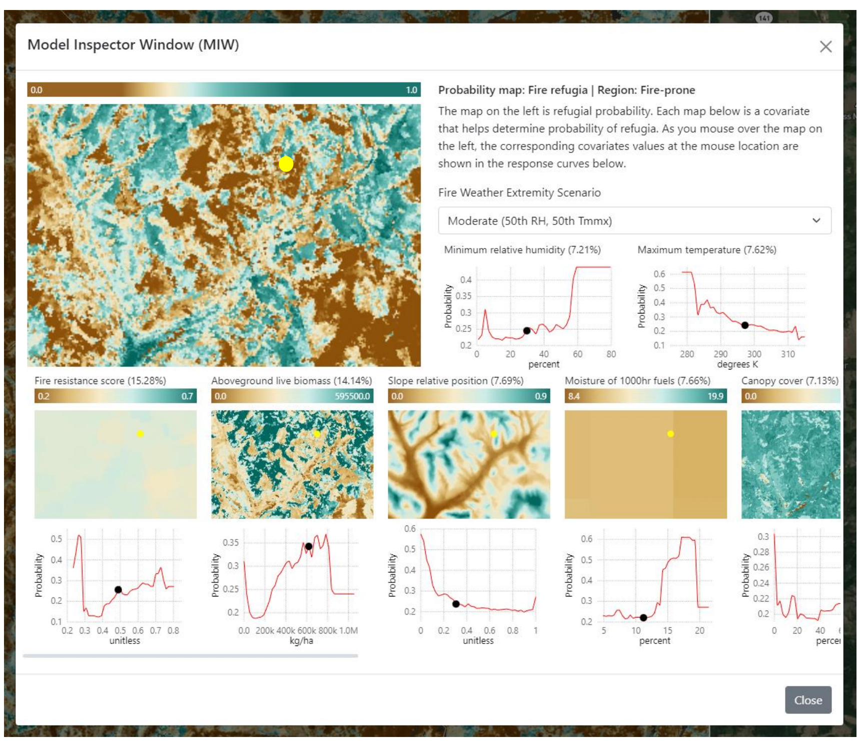


Figure 2. The Eco-Vis Model Inspection Window (MIW) showing drivers of fire refugia for a given pixel.

Appendix 3.

Response functions from topo-climate fire refugia models, from Yang et al. (in prep).